COSMOGENIC CHLORINE-36 EXPOSURE AGES FOR TWO BASALT FLOWS IN THE NEWER VOLCANICS PROVINCE, WESTERN VICTORIA

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An exposure dating method based on the accumulation of cosmic-ray-produced ^{36}Cl has been applied to samples from the Newer Volcanics Province of western Victoria. Cosmogenic ^{36}Cl concentrations indicate exposure ages of approximately 32 kyr BP for the Harman Valley basalt flow from Mt Napier and 59 kyr BP for the basanite ring barrier at Mt Porndon. The results extend the chronology of volcanism at these sites back in time beyond minimum age limits so far obtained from ^{14}C dating of overlying peat deposits. The older ages imply slower rates of soil development on basalt and for re-establishment of drainage systems disrupted by eruptions, and suggest that both processes may also have been influenced by colder and more arid Late Pleistocene climatic conditions. Exposure dating complements dating methods based on soil maturity and ^{14}C and may be applied to good effect on other young volcanic rocks in eastern Australia. In particular, there is scope for dating material either too old to be dated with ^{14}C or lacking associated carbonaceous material, yet too young to be dated with the ^{40}K–^{40}Ar or ^{40}Ar–^{39}Ar methods.

DATING RECENT VOLCANIC ERUPTIONS—EXPERIENCE FROM WESTERN VICTORIA

The difficulties of dating young lavas and volcanic landforms are well known. The geochronological techniques most commonly applied, the radiocarbon and K–Ar/Ar–Ar methods, are not ideally suited to dating volcanic rocks in the 0–100 kyr age range.

The radiocarbon method cannot be used to date volcanic rocks directly. Instead, age constraints must be obtained from stratigraphically related carbon-bearing deposits such as buried soils, lake and river sediments overridden by lava, basal sediments in lakes and swamps dammed by ash or lava, and burned trees. Ages obtained from materials such as these provide only limiting constraints, that may bracket actual eruption ages very loosely. The demonstrated age limit for radiocarbon dating is ~50–60 kyr (*c.* 10 half-lives), a consequence of contamination in sample preparation and limits to measurement efficiency. Moreover, samples of this age and older are commonly found to give apparent ages as low as 30–40 kyr unless stringent care is taken to remove material contaminated by small amounts of younger carbon. Contamination with 'old' carbon is also possible, as in the case of hard water effects, and can also lead to incorrect age estimates.

There has been a long history of attempts to date the youngest volcanic landforms of the Newer Volcanics Province in western Victoria using the ^{14}C method. Gill and co-workers produced age estimates for two of the youngest volcanic features, Mt Eccles and Mt Napier, and their associated basalt lava flows. They obtained minimum limiting ages for the lavas by dating basal peat in Condah Swamp and Buckley's Swamp, drainage basins formed when lava dammed antecedent water-courses (Figs 1, 2). Ages of 6325±120 yr BP and 7240±140 yr BP were obtained for Mt Eccles and Mt Napier respectively (Gill & Gibbons 1969; Gill & Elmore 1973). As minimum limits, these have since proved to be far from close bounds. In a more recent study, Head et al. (1991) obtained minimum limiting dates of 26 240±480 yr BP and 27 510±240 yr BP from lake muds and underlying peat in Condah Swamp and Whittlebury Swamp, both dammed by the Mt Eccles flow. The difference between the two sets of limiting dates, obtained on similar materials from similar stratigraphic contexts can only be ascribed to diachronous onset of sedimentation across the irregular floors of the swamps. Sedi-

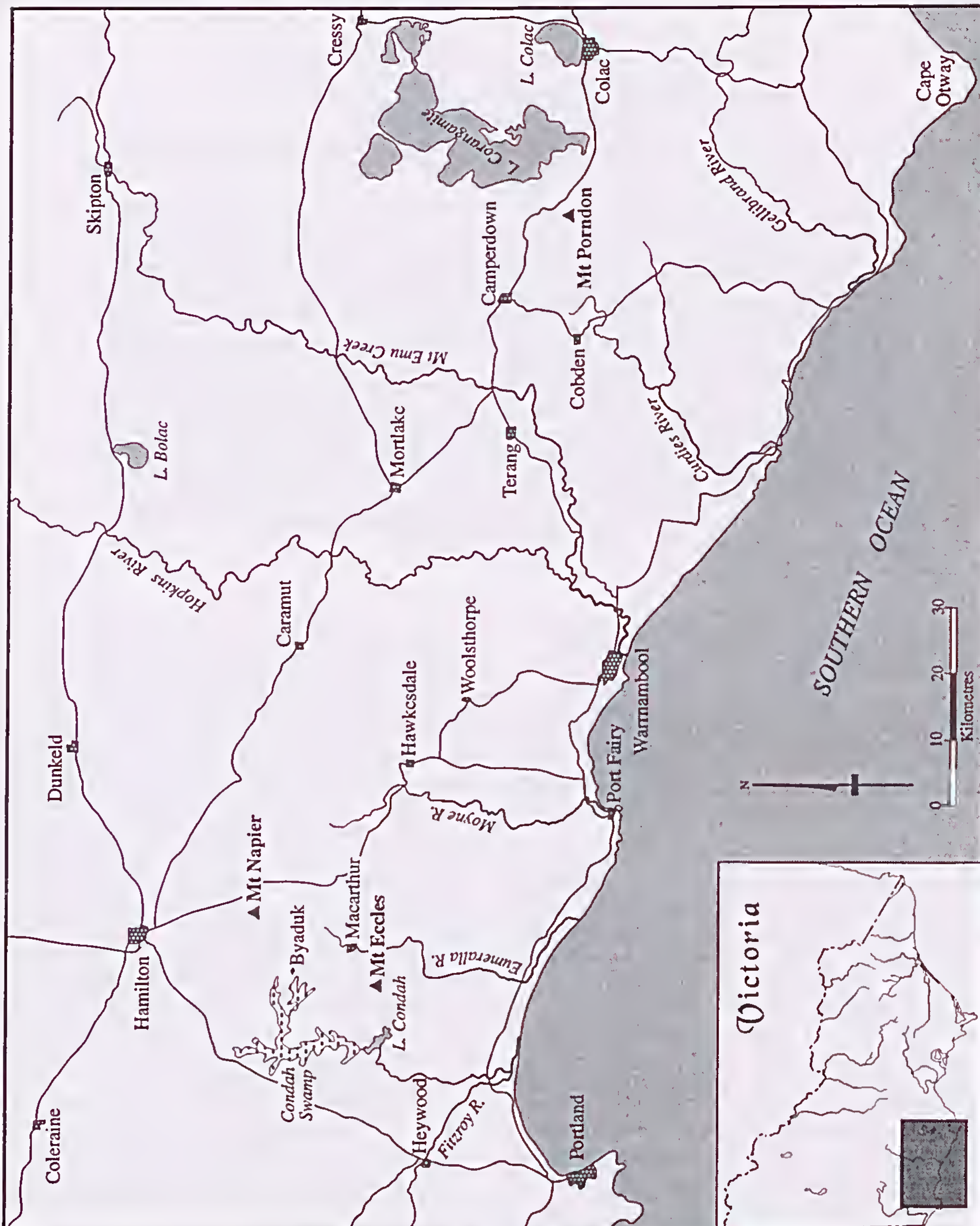

Fig. 1. Location map of western Victoria, showing field sites.

ment thicknesses are reported to vary by more than 4 m in the swamps surrounding Mt Eccles, and it must be assumed that Gill and co-workers were unfortunate in choosing to sample areas of comparatively recent sediment accumulation.

Peat near the northern margin of Condah Swamp is reported by Ollier (1981) to overlie the Harman Valley basalt from Mt Napier (Fig. 2). If this deposit is contemporaneous with the *c.* 27 kyr BP basal peats dated by Head et al., the Harman Valley basalt flow must also be older than 27 kyr BP. It is possible, however, that the onset of sedimentation following damming of the valley was delayed at this site too and that this peat is much younger than the flow which it overlies.

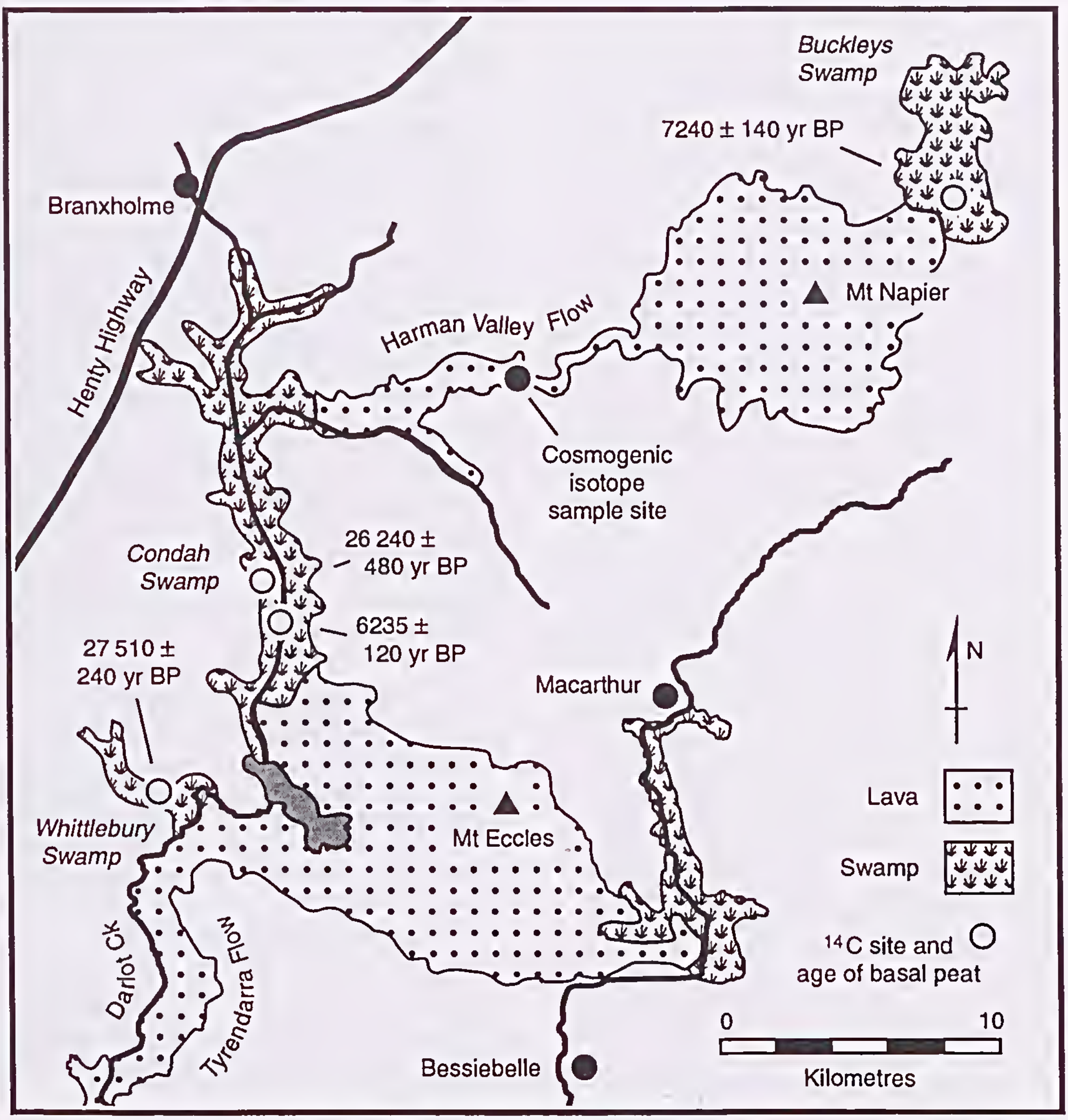

Fig. 2. Detailed site map of Mt Napier and Mt Eccles, showing sample site and sites of cores taken in previous studies for radiocarbon dating.

The 'old' ages obtained by Head et al. are in broad agreement with a very imprecise age of 28^{+21}_{-4} kyr BP for carbonaceous matter in soil beneath scoria from Mt Eccles (Ollier 1981), a maximum limiting age for this eruption. A final, unresolved puzzle in the radiocarbon story is an age of 19.3 kyr BP for wood recovered from fluvial gravels beneath the Tyrendarra lava flow from Mt Eccles (Gill 1979) (Fig. 2). This should represent a maximum age bracket for the Tyrendarra flow and thus conflicts with the 25–27 kyr BP minimum limits referred to above. Although the Tyrendarra flow is known to extend out to sea (and must therefore have been erupted at a time of lower sea-level; Gill 1979) the existence of a gravel bed-load stream at 19 kyr BP and the occurrence of wood in its gravels present a palaeoenvironmental puzzle which casts some doubt on the accuracy of this date. Environmental reconstructions for this period of peak glacial-stage conditions suggest a cold arid climate with lower streamflow than present, and a predominantly grassland vegetation with less tree cover from which the dated wood might have been derived (D'Costa et al. 1989). Whatever the resolution of the conflicting results, the difficulty of establishing consistent and closely-bracketing age constraints on volcanic landforms with the radiocarbon method is evident. This point is further emphasised by the lack of radiocarbon age control on the lava flow at Mt Porndon, the second site selected for study in this work.

The ^{40}K–^{40}Ar and ^{40}Ar–^{39}Ar methods have the advantage over the ^{14}C method of being directly applicable to volcanic rocks. However, there are a number of well-known problems in applying them to basalts in the ~10^4–10^5 yr age range, and few attempts have been made to use them to date the youngest lavas of the Newer Volcanics. Difficulties in dating very young lavas with K–Ar techniques stem from the minute amounts of radiogenic ^{40}Ar produced in such short time-spans. Even in alkali basalts such as those of Mt Porndon and Mt Napier, with K_2O contents of 1.2–1.3%, the amount of radiogenic ^{40}Ar produced in 10^4 years, ~10^8 atoms per gram, is likely to be small compared to the amount of atmospheric ^{40}Ar trapped by the basalt during eruption. Radiogenic ^{40}Ar may only amount to a few per cent of the total ^{40}Ar released from such samples during isotopic analysis. Quantifying such small amounts of radiogenic ^{40}Ar to obtain accurate age estimates requires accurate subtraction of the overwhelming non-radiogenic background. Moreover, simple subtraction procedures cease to be valid if the background component is isotopically fractionated, or if phenocrysts or xenocrysts containing an additional ^{40}Ar-rich mantle-derived component are present in the sample. Thus, although the ^{40}K–^{40}Ar and ^{40}Ar–^{39}Ar methods almost entirely underpin the chronology of the older lavas in the Newer Volcanics Province (McDougall et al. 1966; McDougall & Gill 1975), there has been little success in applying them to the youngest flows. For example, samples of olivine basalt from Mt Porndon analysed by Henley & Webb (1990) gave very low radiogenic and very high atmospheric Ar components, with apparent ages of 0.3±0.6 Myr and 0.26±0.6 Myr, to which the authors ascribed little chronological significance.

Several other dating methods can be applied to young volcanic landforms. Luminescence techniques (thermoluminescence and optically-stimulated luminescence) have been successfully applied to soils baked when over-run by lava, and to quartz in sub-volcanic sediments. Provided well-bleached sub-volcanic material is sampled, luminescence techniques can give direct age estimates for volcanic events. For example, Smith & Prescott (1987) obtained a thermoluminescence age of 4.9±0.5 kyr BP for baked dune sand over-run by basalt at Mt Schank. This result provides much tighter age control on the eruption of Mt Schank than a limiting radiocarbon date of 18.1 kyr BP on underlying charcoal (Polach et al. 1978) and marks what is likely to be the youngest activity in the Newer Volcanics Province. Another, even more direct dating technique which can be applied is surface exposure dating, based on the accumulation of rare, cosmic-ray-produced isotopes in volcanic rock surfaces.

EXPOSURE DATING WITH COSMOGENIC RADIOISOTOPES

Rock freshly exposed at the earth's surface begins to accumulate cosmic-ray-produced radionuclides such as ^{36}Cl, ^{26}Al and ^{10}Be, whose abundances can be used as the basis of an exposure dating method. The penetration depth of the radiation producing these nuclides is a few metres, hence lavas, extruded onto the earth's surface from much greater depths, arrive with initial isotopic concentrations essentially equal to zero. With this simplification, exposure ages can be determined by comparing cosmogenic nuclide concentrations to their production rates. Accumulation is described by the equation:

$$N = {}^{P}/_{\lambda}(1 - e^{-\lambda t}) \qquad (1)$$

where N is the abundance of the radioisotope (^{36}Cl

in the cases described below), P its production rate, λ the decay constant and t the exposure age. Provided P and λ are known and N measured, the exposure age can be calculated directly. For equation (1) to be valid, the surface must have been continuously exposed in a stable orientation, without erosion, throughout the exposure period. In the case of basalt lavas, the preservation of glassy selvedges, pahoehoe and other distinctive textures can be used to identify surfaces which have suffered negligible erosion. Care must be taken, however, to ensure that these features mark the topmost surface of a flow and have not been uncovered from beneath overlying flow sheets. Likewise, the possibility of cover by younger soil or sediment, especially volcanic ash, must always be evaluated, because any cover of the sample surface in the past will have reduced the cosmic ray flux reaching it. To obtain accurate exposure ages, isotope production rates must also be known. Current calibrations are largely based on cosmogenic isotope measurements on independently dated surfaces (e.g. Nishiizumi et al. 1989; Cerling 1990; Kurz et al. 1990; Zreda et al. 1991; Stone et al. 1996). Details of the cosmic ray reactions responsible for ^{36}Cl production and their calibration are discussed in the Results section below.

Cosmogenic isotope methods have already been widely applied to dating basalts. The first measurements of terrestrial cosmogenic ^{3}He were made on Hawaiian lavas (Craig & Poreda 1986; Kurz 1986) and basalts have since been used extensively in calibrating ^{3}He, ^{21}Ne and ^{36}Cl production rates (e.g. Cerling 1990; Zreda et al. 1991; Poreda & Cerling 1992). Cosmogenic nuclide measurements on basalts have also been used to assess volcanic hazards (Zreda et al. 1993) and date catastrophic floods (Cerling 1990). To illustrate the potential of these methods for dating young Australian basalts and resolving ambiguous age estimates from ^{14}C dating, we present below exposure age estimates for two lavas of the Newer Volcanics Province in western Victoria.

SAMPLING AND METHODS

Sample sites

Samples were collected from the basalt ring barrier surrounding the Mt Porndon cinder cone near Colac and the Harman Valley flow from Mt Napier, south of Hamilton (Fig. 1). At Mt Porndon, a sample was collected from a high point on the crest of the western segment of the basaltic ring barrier surrounding the cinder cone (Fig. 3). The ring crest at the sample site rises steeply some 20 m above subdued stony rises on its outer side and a collapsed lava disc, partly overlain by scoria, on its inner side. Except in a few places on the eastern rim where the crest is mantled by cinders or overrun by small flows, the ring barrier consists of fresh, deeply-jointed outcrop with no regolith mantle. The steep flanks of the sample site would have ensured that any ash deposited on the top surface would have been shed rapidly. Although the Mt Porndon basalt is known to post-date both the Purrumbete maar eruption and early sediments in Lake Corangamite (Ollier & Joyce 1986), there are no precise numerical age constraints on its eruption. Ollier & Joyce (1986) assigned it to the Eccles regolith-terrain unit, for which they estimated an age younger than 100 kyr BP. It is clearly younger than surrounding, subdued, soil-covered (and cleared) stony rise country—the Rouse regolith-terrain unit of Ollier & Joyce (1986), broadly equivalent to the the Girringurrup Land System of Gibbons & Downes (1964). The age of this older landscape unit is estimated at between 0.3 and 2 Myr based on the K–Ar ages of McDougall & Gill (1975) and Ollier (1985), and is a loose upper limit to the age expected from exposure dating of the Mt Porndon basalt.

A second sample was collected from the Harman Valley flow, derived from Mt Napier (440 m). The sample was collected from the top of a regolith-free tumulus on the flow. As for the sample from Mt Porndon, it was collected from a surface judged likely to have rapidly shed any ash cover from subsequent eruptive activity. The series of events that formed the Mt Napier volcanic complex (see, for example, Whitehead 1991) disrupted local drainage to produce Buckley's Swamp, a ~30 km^{2} area upstream of the complex, and small swamps downstream where tributaries were blocked by the Harman Valley flow. If peat described by Ollier (1981) as overlying the Harman Valley flow is contemporaneous with basal peat in Condah Swamp to the south (Fig. 2), the ^{14}C age of 26.2±0.5 kyr BP obtained in Condah Swamp would provide a minimum age limit for the sample analysed here. However, it is also possible that peat overlying the Harman Valley flow is substantially younger than the basal deposits in Condah Swamp and places no strong constraint on the relative ages of the Mt Eccles and Mt Napier eruptions. Cosmogenic isotope methods may be useful in dating the full sequence of events in the area in future.

Both samples consist of frothy vesicular basalt with surface textures judged to indicate negligible erosion. Details of the sample locations, including latitude and altitude, which influence the intensity of the cosmic ray flux, and sample thicknesses, which determine cosmic ray attenuation and hence isotope production rates, are given in Table 1.

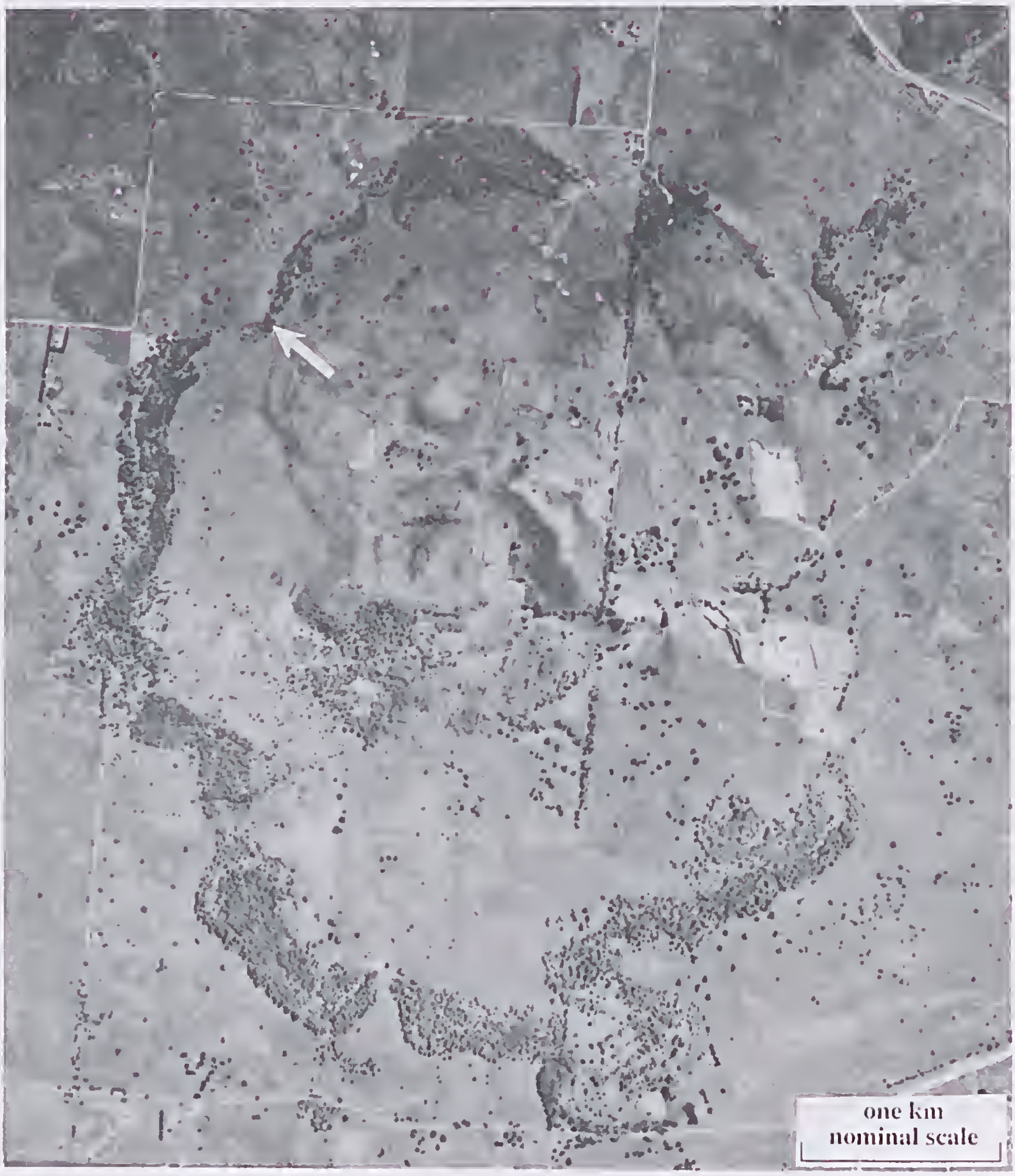

Fig. 3. Sample site and basaltic ring barrier at Mt Porndon. From a black-and-white vertical air photo (Heytesbury North Project, Run 3, 23 November 1969) reproduced by kind permission of Land Victoria, 1997.

Site	Latitude	Effective geomagnetic latitude[A]	Longitude	Altitude (m)	Thickness (cm)/(g cm^{-2})
Mt Napier	37°55′S	42°45′S (0–32 kyr)	141°55′E	85 m	5.0/13.5
Mt Porndon	37°19′S	42°35′S (0–59 kyr)	143°16′30″E	190 m	5.5/15

Table 1. Site and sample details. [A]Latitude at which geomagnetic shielding of the cosmic ray flux equals the time-averaged shielding at the sample site. Chlorine-36 production rates have been scaled with respect to this latitude to correct for variation of the geomagnetic dipole strength during the sample exposure period (see text).

Chlorine-36 analyses

The method used to extract and purify chloride from the samples is described by Stone et al. (1996). Prior to extraction, the crushed samples were leached twice in hot 2% HNO_3 and rinsed thoroughly to remove secondary carbonate and all traces of meteoric chloride and ^{36}Cl contamination. Isotopic analysis of ^{36}Cl was performed by accelerator mass spectrometry (AMS), using the ANU 14 UD Pelletron (Fifield et al. 1990, 1994). Chloride was measured on the samples by ion chromatography after pyrohydrolytic extraction (Evans et al. 1981). Major element concentrations were measured by X-ray fluorescence. Trace neutron-producing and absorbing elements (U, Th, Gd, Sm, B) were measured by ICP-MS. A blank processed in parallel with the samples, using the same amount (~1.15 mg) of ^{36}Cl-free carrier and identical chemical procedures, was found to contain $2\pm1\times10^4$ atoms ^{36}Cl, negligible in comparison to the $2–5\times10^6$ atoms ^{36}Cl extracted from the samples.

Major elements (% wt)		
	Mt Napier	Mt Porndon
SiO_2	51.3	50.3
TiO_2	2.27	2.26
Al_2O_3	15.4	14.8
Fe_2O_3[A]	9.29	10.4
MnO	0.11	0.12
MgO	6.54	8.43
CaO	9.68	8.94
Na_2O	3.87	3.68
K_2O	1.23	1.29
P_2O_5	0.10	0.03
H_2O	0.5	0.5
CO_2	0.0	0.0
Cl	16±3 ppm	26±5 ppm
Trace neutron producers and absorbers (ppm)		
B	10±2	10±2
Gd	6±2	10±2
Sm	6±2	10±2
U	0.3±0.2	0.3±0.2
Th	1.0±0.5	1.0±0.5

Table 2. Chemical composition of samples. [A]Total Fe as Fe_2O_3.

RESULTS

Chlorine-36 concentrations for the two samples and details of their target chemistry and neutron absorption properties are given in Table 2. In whole-rock samples such as these, ^{36}Cl is produced by high energy cosmic ray spallation reactions with K and Ca, capture of cosmic ray-produced secondary neutrons by ^{35}Cl, and to a small degree, by reactions involving cosmic-ray muons. To derive age estimates from the ^{36}Cl concentrations in Table 2, local production rates for these reactions are required. For high energy spallation reactions on Ca and K, we adopt the calibrations of Stone et al. (1996) and Evans et al. (1997) respectively. Production by thermal neutron capture on ^{35}Cl is based on the treatment of Liu et al. (1994), as calibrated by Phillips et al. (1996). A small fraction of the total ^{36}Cl production in the samples is due to negative muon capture by Ca and K isotopes. For the Ca reaction, we adopt the rate given by Stone et al. (1997). The analogous contribution from K has not yet been calibrated independently, and is taken as 5% of the total ^{36}Cl production from K at sea level, in keeping with the assumption used by Evans et al. (1997) when calibrating the K spallation rate. The accuracy of this assumption has a negligible effect (less than ±1%) on the calculated ages. The calibrations referred to above apply to production by the cosmic ray flux at sea level and latitudes >50°. Rates have been scaled to the altitude and latitude of the sample sites in Victoria using the procedures given by Lal (1991), and then corrected for variations in the cosmic ray flux due to changing geomagnetic dipole strength during exposure, as discussed below. Small corrections

	Mt Napier	Mt Porndon	
[^{36}Cl]	$1.87\pm0.12\times10^5$	$3.70\pm0.25\times10^5$	(atom/g)
P Ca Spallation	3.35±0.12	3.40±0.12	(atom/g/yr)
P K Spallation	1.82±0.12	2.10±0.14	(atom/g/yr)
P Ca(μ^-,α)^{36}Cl	0.32±0.06	0.31±0.06	(atom/g/yr)
P ^{39}K(μ^-,p2n)^{36}Cl	0.09±0.03	0.10±0.03	(atom/g/yr)
P ^{35}Cl(n,γ)^{36}Cl (thermal neutrons)	0.40±0.10	0.66±0.16	(atom/g/yr)
P ^{35}Cl(n,γ)^{36}Cl (epithermal neutrons)	0.09±0.02	0.15±0.03	(atom/g/yr)
P Total	6.09±0.21	6.75±0.25	(atom/g/yr)
Altitude/Latitude scaling (spallation)^A	1.04	1.14	
Altitude/Latitude scaling (muon reactions)^A	1.00	1.05	
Thickness correction (spallation)^B	0.96	0.96	
Thickness correction (thermal neutrons)^B	1.32	1.32	
Thickness correction (epithermal neutrons)^B	1.06	1.07	
Best estimate exposure age (including geomagnetic corrections)	31.9±2.4	58.5±5.0	(kyr)
Exposure age (uncorrected for magnetic variation)	33.6	62.3	(kyr)
Exposure age (Phillips/Liu production rates)	27.2±2.3	50.8±4.5	(kyr)

Table 3. Exposure dating results. ^{A}Scaling factors (relative to production rate at sea level and latitude >60°) calculated with respect to the effective geomagnetic latitude of the sample sites. Scaling factors with respect to geographic latitude of the sample sites are 0.99 and 1.08 for production by spallation at Mt Napier and Mt Porndon, respectively, and 0.95 and 0.99 for production by muons. ^{B}Production rate relative to 2Π, thin surface exposure.

have also been included to take account of cosmic ray attenuation within the 5–6 cm thick samples and to allow for disequilibrium between neutron production and absorption at the outcrop surfaces (Liu et al. 1994). Because both samples were collected from high-standing features above relatively flat horizons, no corrections are required for obstruction of the incoming cosmic-ray flux. The fully corrected production rates for the samples, P in equation 1, are given in Table 3.

With these values, equation 1 gives an age of 32±3 kyr BP for the Harman Valley lava, and 59±5 kyr BP for the Mt Porndon ring barrier (Table 3). The uncertainties in these ages reflect both the statistical precision of the AMS measurements (±5–7%) and remaining uncertainty in the calibration of the various ^{36}Cl production rates (±5–15%). An alternative set of values for the surface production rates of ^{36}Cl from Ca and K has been given by Phillips et al. (1996). These authors obtained a higher production rate from Ca and a lower rate from K than those underlying the rates shown in Table 3. Adopting the values of Phillips et al. (1996) gives slightly younger ages for the samples, which for completeness at this stage in our understanding of cosmogenic isotope production are also listed in Table 3. The two sets of ages calculated differ by 13–15%, which, though greater than the analytical uncertainties, is less than the discrepancies between the calibrations. Because the production rate from Ca estimated by Phillips et al. is higher, and that from K lower, than the rates used here, the discrepancies tend to cancel when applied to whole-rock samples containing both elements.

The ages have been calculated to allow for past changes in the earth's geomagnetic field intensity, which modulates the cosmic ray flux at low to mid latitudes (cf. Clark et al. 1995). At times of high dipole field strength, the cosmic ray flux decreases at these latitudes. Conversely, at times of low strength, a greater fraction of the primary cosmic ray flux reaches the atmosphere. (Similar changes occur through the 11-year solar cycle, but are well averaged over thousand-year calibration and sample exposures.) At the latitude of the sites in western Victoria, the ^{36}Cl production rate is likely to have varied by up to +12% and −10% relative to its present value for short periods in the past ~100 kyr, assuming the geomagnetic intensity record of Meynadier et al. (1992). The effect on time-averaged ^{36}Cl production is considerably smaller, due to the integrating nature of cosmogenic isotope build-up and the compensating effect of oscillations between high and low field intensity. To correct for changes in the cosmic ray flux we have used the method of Nishiizumi et al. (1989) to determine effective geomagnetic latitudes for the sites (i.e. latitude in the present field where the cosmic ray flux equals the time-average received at the sample site; see also Clark et al. 1995). Noting that the production rates of Stone et al. (1996) and Evans et al. (1997) are calculated with allowance for geomagnetic changes, we believe that the magnetically corrected results in Table 3 give the most accurate estimates of exposure age for the samples. These ages (31.9 and 58.5 kyr BP) are younger than the uncorrected estimates shown in Table 3, reflecting the fact that the dipole field strength averaged over the past 30–70 kyr BP was lower, and the cosmic ray flux higher, than at present.

The ages obtained for the basalts are consistent with existing, broad age constraints. The cosmogenic isotope age for the Harman Valley flow is older than the oldest radiocarbon age of 26 240± 480 yr BP obtained from basal peat in Condah Swamp (Head et al. 1991), which is consistent with the suggestion that deposits resulting from the damming of Condah Swamp overlie the Harman Valley basalt. If so, then a reasonably tight age bracket is obtained for the main eruption of Mt Eccles that blocked Darlot Creek to produce Condah Swamp. The timespan separating the Harman Valley eruption and the damming of Condah Swamp (bracketing the Mt Eccles eruption) would be less than the 6000 year apparent difference between the cosmic ray exposure age and radiocarbon age, because of the propagation of atmospheric $\Delta^{14}C$ variations into radiocarbon age estimates. Around 30 kyr BP, Mazaud et al. (1991) calculate that uncalibrated radiocarbon ages will underestimate true ages by ~2 kyr and Bard et al. (1990) present data indicating an offset of 2–3 kyr. This would place the eruption of the Mt Eccles basalt between the calibrated ^{14}C age of ~28 kyr BP and the ^{36}Cl age of the Harman Valley flow, 32 kyr BP. The age obtained for Mt Porndon is younger than, hence consistent with, the 100 kyr age limit suggested by Ollier & Joyce (1986) for the Eccles regolith-terrain unit and significantly younger than age estimates for the stony rise country which it overruns.

DISCUSSION

The exposure ages obtained in this study confirm the impression conveyed by ^{14}C re-dating in the Newer Volcanics Province (Head et al. 1991), that the youngest events in the province are significantly older than was originally believed. This follows a similar reappraisal of the age of phreatomagmatic activity at Mt Gambier, where an interpreted ^{14}C age of ~4.3 kyr BP (Blackburn et al. 1982) has been revised upwards to greater than 28 kyr BP (Leaney et al. 1995). The age revisions in the Western District have implications for the interrelationship between lavas and drainage patterns, the soils/weathering relative chronology for land surfaces in the region and for the study of past environments and human occupation.

The overall pattern of landscape evolution in the Newer Volcanics province shows many examples of lavas disrupting drainage (e.g. Ollier 1985). Many of the earlier episodes have been overcome and drainage re-established after millions of years of weathering. The effects around Mt Napier and Mt Eccles, involving lava damming and the creation of numerous swamps and lakes, remain prominent after ~30 kyr. On these flows, and in the older 'stony rise' landscapes into which they are set, drainage remains largely internal and broad-scale topographic control has not yet been re-established. Now that it is apparent that both the Mt Eccles and Mt Napier flows date back to ~30 kyr BP, the limited degree of drainage development can also be attributed to more arid climatic conditions that prevailed in the region from at least 20 kyr BP through to 11.5 kyr BP (D'Costa et al. 1989).

Time constraints on soil development in the district can also now be refined. Both the Napier and Mt Porndon basalt surfaces remain fresh and essentially soil-free, compared to a limited degradation of stony rises and infilling of hollows by weakly developed stony loam soils on surrounding land surfaces. The ~60 kyr BP age for the Mt Porndon lava demonstrates that the absence of soil development is not a consequence of an extremely young substrate, as would have been inferred when it was believed that the youngest flow surfaces in the district were Holocene in age (Gill & Gibbons 1969).

An additional conclusion that can be drawn from the ages now established for the Mt Napier and Mt Porndon eruptions is that the limited evidence for pre-late Holocene human occupation (e.g. Ross 1985) and the evidence for intensification of human activities in the district in the late Holocene (e.g. Lourandos 1983) cannot be attributed to volcanic activity.

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